Strange Quark as a probe for new physics in the Higgs Sector

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U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Why Strange Quarks to probe the Higgs Sector?

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- Yukawa coupling of the SM Higgs boson to the **third generation of fermions has been clearly established** at the LHC

- ATLAS and CMS have recently reported **evidence that the Higgs boson decays into muons**
  - First experimental indication that the Higgs boson interacts with second-generation leptons
  - **Not yet a complete exploration of second-generation Yukawa couplings**
    - Rare c/s Higgs decays modes are very challenging (nearly impossible to detect with the current detector capabilities)
    - New **algorithms for the identification of c-quark jets are becoming available** and have enabled searches for **Higgs to c quarks**
    - **Less literature**, instead, is available about searches of **Higgs decays to light quarks**
      - **No projections available at future machines**
      - **They may remain out of direct experimental reach unless they are enhanced compared to SM expectations**

Flavor violating Higgs decays

- When considering **BSM models**, the possibilities for testing the Higgs coupling to strange quarks open up

- **2 Higgs Doublet Model (2HDM) as an example**: one doublet (approximately identified as the 125 GeV Higgs) couples mainly to the third generation, while the second doublet couples mainly to the first and second generation

    - Largest production mode of the neutral Higgs bosons would be from a $c\bar{c}$ initial state, while the charged Higgs bosons would be dominantly produced from a cs initial state.

    - The most interesting decay modes include $H/A \rightarrow cc, tc, \mu\mu, \tau\mu$ and $H\pm \rightarrow cb$, $\boldsymbol{cs}$, $\mu\nu$.

Strange Tagging

- Tagging strange quark jets would:
  - allow us to open new opportunities for h → $s\bar{s}$ searches
  - if used in conjunction with c-tagging, it would also allow to probe new physics models
    - $H\pm \rightarrow cs$ (or bs? SLAC-R-728)
      - increased branching ratio foreseen in the 2HDM model

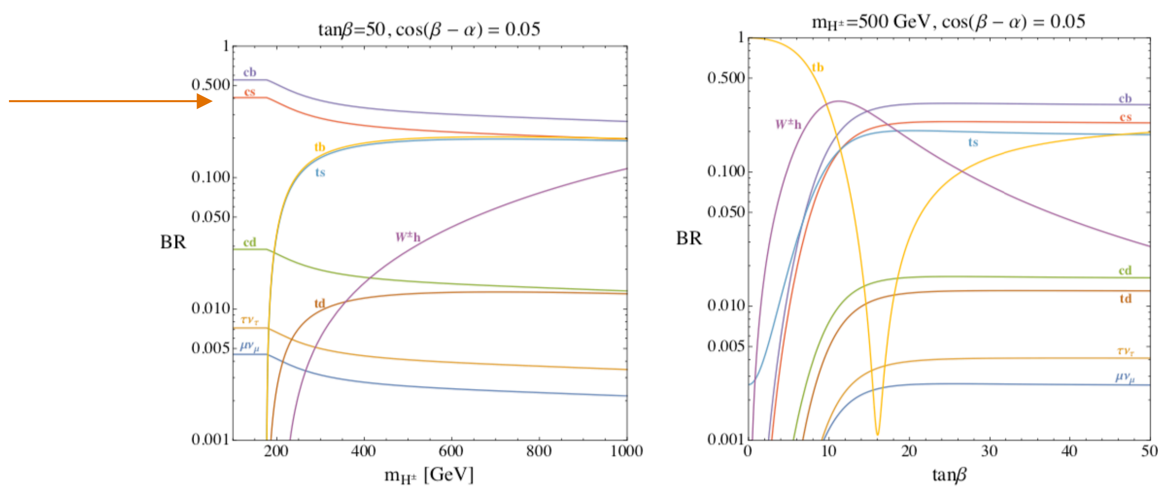

FIG. 6: Branching ratios of the charged Higgs $H^{\pm}$ as a function of the charged Higgs mass $m_{H^{\pm}}$ for fixed $\tan\beta = 50$ (left) and as a function of $\tan\beta$ for fixed Higgs mass $m_{H^{\pm}} = 500$ GeV (right). For both panels, we fix $\cos(\beta - \alpha) = 0.05$.

"*Collider Signatures of Flavorful Higgs Bosons*", W. Altmannshofer et al., Phys Rev. D94 (2016), 11, 115032.

Experimental Handles for Strange Tagging

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- The goal is to **discriminate strange jets from u/d jets** (discrimination from c/b happens through c/b tagging)
- The challenge is that **strange hadrons** are certainly **produced from the fragmentation of strange quarks**, but they are **also produced frequently in the fragmentation of u/d quarks** (typically with a lower fraction of the jet's transverse momentum x)
  - Identical QCD and electromagnetic interactions, but different hadronization and subsequent decay processes
  - The main idea behind strange taggers is that strange quarks mostly hadronize to prompt kaons that carry a large fraction of the jet momentum
  - A strange-quark jet contains on average a **higher ratio of neutral kaon energy** (more energy in the HCal) **to neutral pion energy** (more energy in the ECal) wrt a down-quark jet
    - One of the main handles used in arxiv:2003.09517v1 (presented in EF2)

- It is clear that **PID capabilities** to discriminate between kaons and pions would be very helpful in building a solid strange tagger
  - Lessons can be learned from the SLD experience in tagging strange jets from Z decays (Cherenkov detector with k/pi separation at all momenta)
  - PID has been considered also in arxiv:1811.09636 (see extra slides for some details)

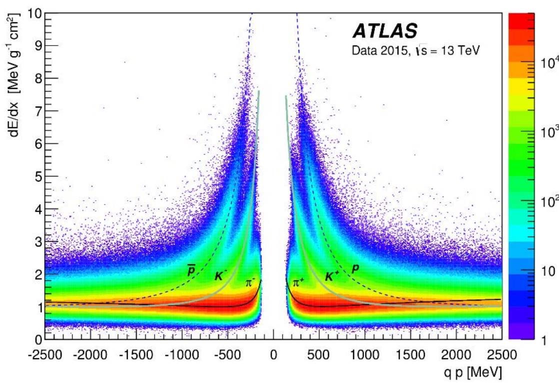
Particle Identification

- **Existing strange tagging** studies suffer from **low efficiency and very large mis-tag probability** from u and d quarks, even when using sophisticated machine learning algorithms

- To complement existing studies (more on this in the next slides), we thought we would put **more emphasis on exploiting Particle Identification**

  - This implies looking at new detector concepts
  - Current general purpose detectors use the well known **d*E*/dx dependence on βγ**, but this only allows to get to good PID up to ~1 GeV
  - Alternatively, as foreseen for the HL-LHC detectors, **timing information** can be used to deduce a **velocity** that, in combination with the standard measurement of **momentum from track curvature in the magnetic field**, yields a measure of the **charged particle mass**.
  - Another very effective way to achieve particle identification is through **Cherenkov detectors**, as done in the ALICE and LHCb experiments at the LHC

Phys. Rev. D 93, 112015 (2016)



In either scenario, **kaons with at least 20% of the jet's transverse momentum x** will have to be identified in order for this to be relevant for strange tagging.

What we would like to do

- We are still in a very early phase of this project (first meeting last week: https://indico.slac.stanford.edu/event/6617/), so much has yet to be defined and we would greatly appreciate inputs from the community as well as help from new collaborators!

Snowmass LoI

> *"More specifically, in the context of Snowmass 2021, we propose to study the feasibility of the measurement of Higgs boson couplings to light quarks, in particular to strange quarks, as of paramount importance to complete the understanding of the Higgs sector. The emphasis will be put on future lepton colliders since the branching ratio for h → ss is below the level of 10-3 [6] in the SM and the measurement requires a large number of Higgs bosons in a very clean environment, but important information on the usage of advanced 4D tracking capabilities can also be learned in the HL-LHC context. This study strongly aims at motivating the development of strange tagging techniques and at providing requirements to future tracking algorithms and timing detectors performance."*

- As a side note: a partially related, but more detector-specific LoI on 4D tracking was also submitted and can be found here
    - If possible, any connection between the two would of course be nice

What samples would we need?

- Signal: **$e^+e^- \rightarrow$ Zh with $Z \rightarrow \nu\nu$ (shown to give highest sensitivity to h->jj)**
  - Account for jet flavour composition

- Backgrounds:
  - Events without h
  - Events in which the h does not decay to jj
  - Events in which the h is not produced in association with two neutrinos
  - $e^+e^- \rightarrow W^+W^-$ (one W decays leptonically and the other hadronically)
  - $e^+e^- \rightarrow \nu\nu qq$ and $e^+e^- \rightarrow qq$ (the quark pair can fake the h).

- What about **$H^{\pm}$->cs** samples? Would be great to get feedback from theorists on which model would be the best to use

- We are familiarizing with the tutorials (in particular the ILC one so far, but we have to wait for the follow-up tutorial to happen, which will be more focused on the analysis)

- We have contacted the MC task force coordinator for technical advices on how to proceed
  - For now we would like to **start looking into truth level information**, we are not paying too much attention to the actual detector, we would mainly like to check the truth info to see how to better discriminate between pions and kaons arising from the original s-quarks rather than from fragmentation of other light quarks, so either ILC or FCC or any other e+e- scenario would be OK as a starting point (whatever has a framework that is easier to use would be our preference!)

Possible Collaborations

- David D'Enterria gave a talk during one of the EF1 meetings on ***Electron Yukawa from s-channel in e^+e^- → Higgs production at FCC-ee*** and during the talk he mentioned that he was working also on H->ss, so we got in touch with him to explore possible collaborations

- Their focus would be on exclusive **H->phi+gamma** decay, rather than the full h->ssbar with jet reconstruction
  - *One expects a handful of such rare decay events with the ~1.5 million Higgs expected at the **FCC-ee***
  - *This direct decay interferes with the (more probable)* ***H->gamma gamma*->gamma phi channel****, and one needs to disentangle the dependence of the yields on k_gamma and k_s (the k_gamma coupling should be known with good accuracy...).*
  - *There are phenomenological studies for the LHC* (in fact we has cited the one from the ATLAS Collaboration), *but neither of us recalled them for e+e-.*
  - He proposed he will take a closer look at it and try to estimate the actual sensitivity to k_s
  - If potentially relevant, and if we are interested in that channel, we carry out together a simulation analysis...
    - Main signal and background samples needed would be the ones mentioned above

  - N.B. **No interest from them on ILC scenario (because of the lower statistics)**

Summary

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ILC Study Questions for Snowmass 2021

- We would like to contribute to increasing our understanding of the **Higgs boson Yukawa coupling to second generation fermions**, with emphasis on **strange quarks**

6 Questions about Higgs boson physics: $e^+e^- \to Zh$

7. Higgs decays to 2 jets. At e^+e^- colliders, Higgs decays to all hadronic modes can be observed directly. Current studies of $h \to b\bar{b}, gg, c\bar{c}$ (e.g., [62]) date from the era before deep learning, and before the understanding of q/g jet separation gained from LHC. What, now, is the optimum method for separating these three decay modes. What systematic errors can be achieved? [miniDST]

8. Higgs decays to light quarks. One can add to the previous question the possibility of Higgs decay to $s\bar{s}$, $d\bar{d}$, $u\bar{u}$. What limits on these modes can be achieved? Can $h \to s\bar{s}$, with $BR = 10^{-4}$ in the SM, be observed? A theoretical study on the discrimination of light quark and gluon initiated jets can be found in [63]. The possibility of observing $h \to s\bar{s}$ is discussed in [54] and in question #12 of Sec. 5. [miniDST]

13. Flavor-violating Higgs decays. What limits can be placed on $h \to \tau\mu$, $h \to bs$, and other flavor-violating fermion combinations? [miniDST]

5 Questions about general e^+e^- event analysis

11. Particle ID. The SiD and ILD detectors do not have dedicated subdetectors for particle ID; however, they can identify kaons by dE/dx measurement or by track timing. Identification of kaons is important for many aspects of e^+e^- physics, including the vertex charge measurement described in the previous question and the reconstruction of τ leptons from their final states. It is then interesting to consider how kaon identification could be improved, for example, using the new timing detector technologies being developed for HL-LHC, and the implications for e^+e^- physics measurements. [miniDST].

12. Strange quark tagging. It would be useful to be able to tag strange quark jets in e^+e^- processes. Studies of $Z \to s\bar{s}$ from the LEP/SLC era can be found in [51, 52]; these use dedicated RICH/CRID particle ID detectors. More recent proposals for strange taggers, for general purpose detectors, are given in [53, 54]. These strategies can surely be improved. [miniDST]

- To do so, we plan to develop a **strange tagger** and provide **inputs to detector instrumentation** that would allow to make such a tagger a reality and open up possibilities for investigating SM Higgs boson decays to strange quarks as well as Higgs flavor violating decays
  - How much would we need to give up on calorimetry in order to have a Cherenkov detector in place?
  - Given the current technology for timing detectors, what level of k/pi discrimination would we reach?

From the Energy Frontier workshop

Instrumentation

- Understand the impact of detector designs on physics
  - Conversely comment on the improvement of physics sensitivity as function of a detector parameters
  - The detectors must maintain excellent precision and efficiency for all basic signatures
  - This performance has to be maintain over an immense range of momentum and angle because the detectors must excel at measuring both the relatively low energy decay products of the Higgs boson and the highest energy particles ever produced at an accelerator
  - For example: the 100 TeV pp collider will produce particles with momenta ranging between a few GeV and 20 TeV over $0<|\eta|<6$.
    - These momentum and angular ranges are ten times and twice those achieved at the LHC!
- The proposed collision energies and data rates of the next generation of Energy Frontier colliders impose unprecedented requirements on detector technology.
- A few examples motivated by Higgs Physics at future colliders, which were considered for the DOE Basic Research Needs exercise for future instrumentation
  - Low-mass, high-granularity, radiation-hard, tracking detectors with picosecond timing
  - High-granularity, radiation hard, imaging calorimeters with picosecond timing
  - Integrated high-bandwidth, low-latency, ML-ready trigger and readout

Extra Slides

Existing study by J. Duarte-Campderros, G. Perez, M. Schlaffer, and A. Soffer

https://arxiv.org/pdf/1811.09636.pdf

SLAC

In this letter we propose using a strangeness tagger, inspired by Z → ss measurements at the DELPHI [24] and SLD [25] experiments, for probing the Higgs coupling to the strange quark via the h → ss decay.

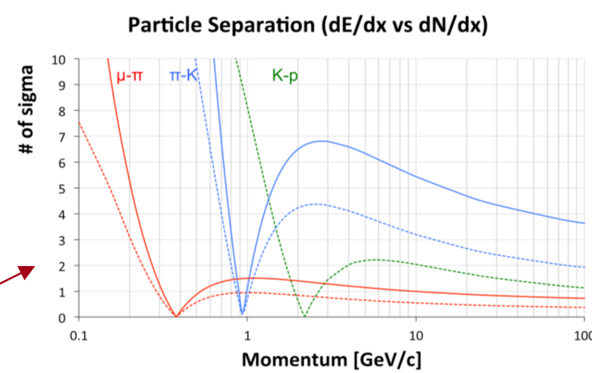
We limit the discussion to lepton colliders, having in mind the International Linear Collider (ILC) [26], the Future Circular Collider in electron mode (FCC-ee) [27], and the Circular Electron Positron Collider (CEPC) [28]. These proposed colliders would run at a center-of-mass energy √s = 250 GeV, where the cross section for associated Higgs production, e+e− → Zh, peaks at σ ≈ 210 fb for unpolarized beams [29, 30]. We therefore adopt this scenario for this letter.

hadrons remains. To exploit this, we define a new jet-flavor variable,

$$J_F = \frac{\sum_H \mathbf{p}_H \cdot \hat{\mathbf{s}}\, R_H}{\sum_H \mathbf{p}_H \cdot \hat{\mathbf{s}}}. \quad (4)$$

Here, the sum is over all hadrons inside the jet, $\mathbf{p}_H$ is the momentum vector of the hadron H, R_H is its quantum number or numbers in the flavor representation of interest, and $\hat{\mathbf{s}}$ is the normalized jet axis. In our case of a Higgs boson produced approximately at rest and undergoing a $h \to jj$ decay, $|\sum \mathbf{p}_H| \approx m_h/2$, so that the denominator is nonzero, and J_F is well defined. Here and in the following we use $h \to jj$ to denote a Higgs decay into a final state of two gluons or a quark–anti-quark pair.

We further take into account the possibility that the detector has a particle identification (PID) capability, to discriminate pions from kaons. For concreteness we adopt the PID capability of the IDEA drift chamber with cluster counting, which can separate pion from kaon tracks by more than 5 standard deviations in the relevant momentum range [38].



https://link.springer.com/article/10.1140/epjst/e2019-900045-4

We obtain an upper limit on the signal strength of μss < 14 and < 7 for integrated luminosities of 5 and 20 ab^{-1}, respectively. The limit is weakened to μss < 60 for an integrated luminosity of 250 fb^{-1}.

Can these limits be improved (and eventually make this decay mode accessible) with new detector features? How can we better complement these studies? What would be a nice flavor violating Higgs decay benchmark to target?

What is available?

- A set of tutorials is being put in place by the Snowmass MC task force to help new users ramp up (most of these tutorial still have to take place, so we will learn more in the coming weeks)
- The list of samples currently available is here

https://snowmass21.org/montecarlo/energy

MC/Simulation Framework Tutorial Series

We are holding a series of tutorials for a variety of proposed future colliders. The goal of these tutorials is to prepare outside collaborators to conduct physics studies for these machines.

Machine	Date	Link
ILC	Aug 28	https://indico.fnal.gov/event/45031/
CEPC	Sept 8	https://indico.fnal.gov/event/45183/
FCC-ee/hh	Sept 22-23	https://indico.cern.ch/event/945608/
LHeC/FCC-eh	Sep 25	https://indico.fnal.gov/event/45185/
Whizard for e+e-	Sept 28	https://indico.fnal.gov/event/45413/
FCC-ee/hh	Sept 29	https://indico.cern.ch/event/949950/
Muon Collider	Sep 30	https://indico.fnal.gov/event/45187/

Which proposed collider are you responding on behalf of?	What signal/background MC samples have been produced thus far (using either fast or full simulation)?
ILC	generator-level event samples, stdhep format for $\sqrt{s}$ = 250GeV, 350 GeV, 500 GeV, 1 TeV, further samples based on fast simultion (SGV) and full simulation (iLCSoft) are in preparation
CLIC	See: https://twiki.cern.ch/twiki/bin/view/CLIC/MonteCarloSamplesForCLICdet
CEPC	We have full simulation of CEPC ZH and SM background at 240GeV, 350GeV, and Z pole events. See CEPC Note http://cepcdoc.ihep.ac.cn/DocDB/0002/000203/002/CEPCNoteCover.pdf
FCC-ee	A limited number of useful e+e- event samples, processed through full CMS simulation and reconstruction, still exist (though producing again these events won't take very long).
FCC-hh	Full and Delphes samples are listed here http://fcc-physics-events.web.cern.ch/fcc-physics-events/Delphesevents_fcc_v02.php http://fcc-physics-events.web.cern.ch/fcc-physics-events/FCCsim_v03.php
LHeC/FCC-eh	Signal: several Higgs decay modes plus backgrounds
Muon collider	Higgs to bb and b backgrounds

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A	J	K	L	M	N
Which proposed collider are you responding on behalf of?	Can they be accessed by external collaborators? If so, how?	Is any proprietary code required in order to analyze these samples?	Is any documentation available to facilitate analysis of these samples?	How should any publicly-available resources (MC samples/framework) be credited/cited?	How can access to resources which are not publicly-available be obtained? Is full membership within the collaboration required, or is any sort of "light" membership possible?
ILC	If they have access to VO ILC. For full simulation samples an ILD or SiD guest membership will be required.	No	In preparation.	see: "ILC Study Questions for Snowmass 2021" prepared by LCC Physics Working Group	ILD and SiD will offer a guest membership.
CLIC	Access can be granted for CERN account holders, membership to the ILC VO can probably be granted without too much hassle. Files could be transfered to other StorageElements if they allow the ILC vo access, if that would help	No	LCIO API lcio.desy.de, The full simulation is based on the Marlin framework using LCIO for input output. The collections *SelectedPandoraPFOs contain reconstructed particle flow objects that can be used as input to JetClustering, Vertexing or Flavourtagging, depending on the requirements of the analysis. LCFIPlus (https://github.com/lcfiplus/LCFIPlus), FastJet(https://github.com/iLCSoft/MarlinFastJet)	CLIC: http://dx.doi.org/10.23731/CYRM-2018-002 CLICdet: https://cds.cern.ch/record/2254048 ; Full simulation samples: https://arxiv.org/abs/1812.07337, CLICdet delphes card: https://arxiv.org/abs/1909.12728, DD4hep: https://doi.org/10.5281/zenodo.592244; Whizard2	Read access to the CERN EOS space can probably be given to cern account holders.
CEPC	Currently, an IHEP account is needed to access these samples. You can contact us and we will be happy to apply an account for you.	The CEPCsoft is developed from the LCIO-Marlin framework that has been widely used in linear collider studies. You need to have LCIO, Marlin, and ROOT to do the analysis, you can install them individually – or more easily, install the entire CEPC software packages, see http://cepcsoft.ihep.ac.cn/guides/scratch/docs/cvmfs/	Yes, the samples description can be found in http://cepcdoc.ihep.ac.cn/DocDB/0002/000203/002/CEPCNoteCover.pdf. There is also a CEPC software webpage (http://cepcsoft.ihep.ac.cn), describing the overview of all the softwares we use and some illustration. A CEPC notes database (http://cepcdoc.ihep.ac.cn/cgi-bin/DocDB/DocumentDatabase) with plenty of existing analysis can be also used as an indication.	Most of the existing samples are generated/used for the CEPC CDR studies. Thus it can be referred to as the CEPC CDR samples, and simply cite the CEPC CDR. For Full simulation studies, you can cite its general performance validation at: Eur. Phys. J. C (2018) 78:426. (https://arxiv.org/pdf/1806.04879.pdf). For Delphes-based fast simulation studies, the citable is https://arxiv.org/abs/1712.09517.	It is in principle possible
FCC-ee	Possibly on demand, in a way to be defined	No, plain ROOT	No	FCCSW coordinators on behalf of the FCC-ee collaboration	Only need to have access to CERN (lxplus account) and registration to the relevant CERN e-groups.
FCC-hh	Yes, either by subscribing to dedicated e-groups at CERN, or could setup web based but less prefered	no	Yes, https://cds.cern.ch/record/2717892	FCCSW coordinators on behalf of the FCC-hh collaboration	Only need to have access to CERN (lxplus account)
LHeC/FCC-eh	Possibly upon request	No	Only in talks at workshops	https://inspirehep.net/literature/1118165 (update to appear soon)	Light membership is possible
Muon collider	Yes	No	Yes	University of Padova, INFN, ILCSoft	No membership required

From a "quick" look at the various lists, it does not seem that there is any sample suitable for us, so we would need to get in touch with the contact people from the various collaborations

Future meetings

- **Snowmass Community Planning Meeting (5-8 October 2020)**
  - https://indico.fnal.gov/event/44870/

- "***Higgs as a probe of new physics***" breakout session (co-organized by Energy and Theory frontier topical groups)
  - https://indico.fnal.gov/event/44870/sessions/16305/#20201006
  - The focus will be on 2 topics: **Higgs/Flavor** and **Higgs Potential**
  - The idea is to break the 60' session in half, the first half concentrating on flavor, the latter the on Higgs potential (and related things) with **as much discussion as possible**. There will be only few slides with open points to trigger discussion.

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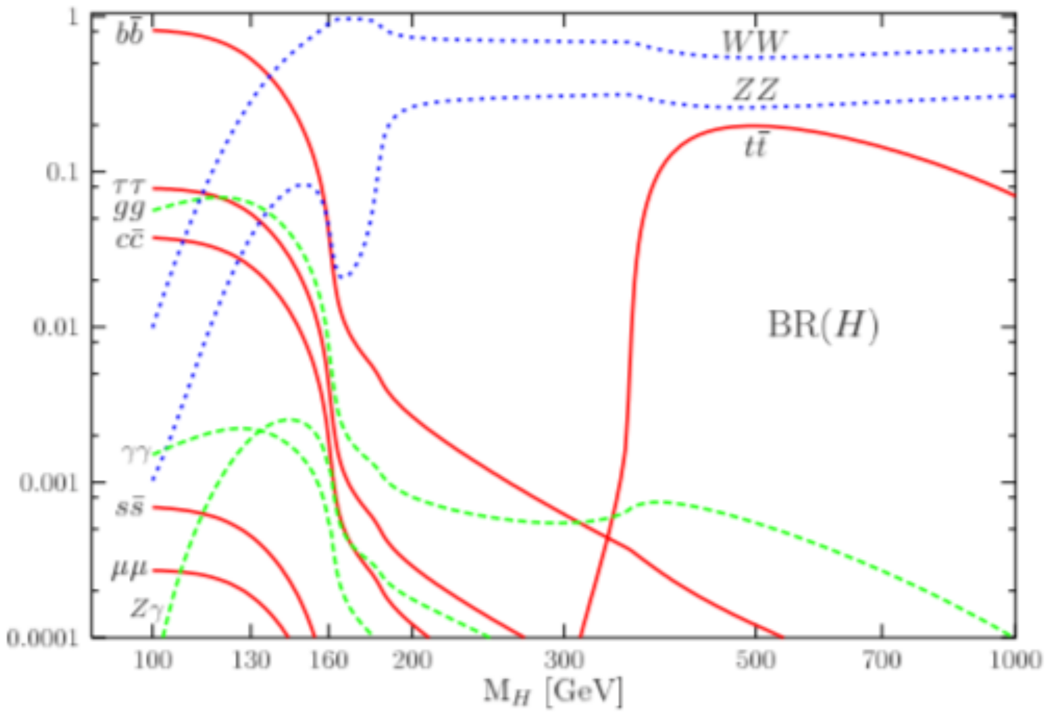

Fig. 1 From [5]: The decay branching ratios of the SM Higgs boson as a function of its mass.

[5] "*Electroweak Symmetry Breaking at the LHC*", A. Djouadi, R.M. Godbole, https://link.springer.com/chapter/10.1007%2F978-81-8489-295-6_5, https://arxiv.org/abs/0901.2030

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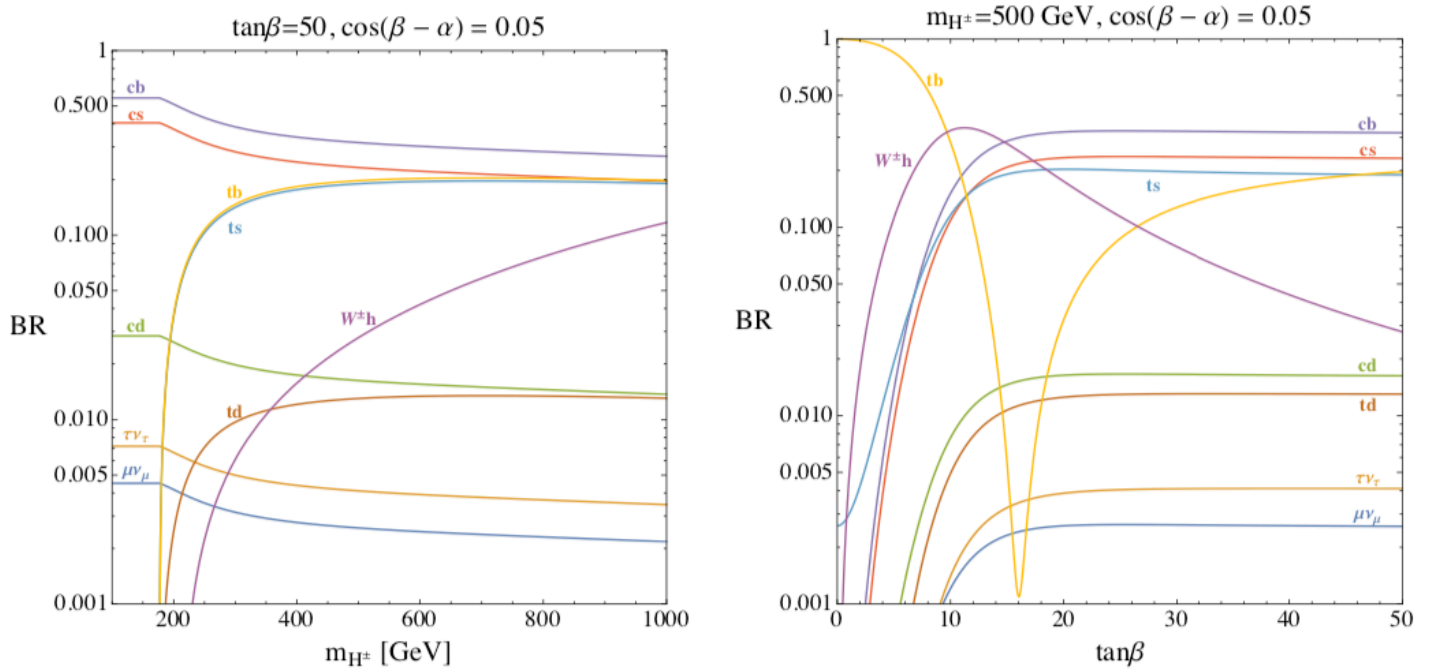

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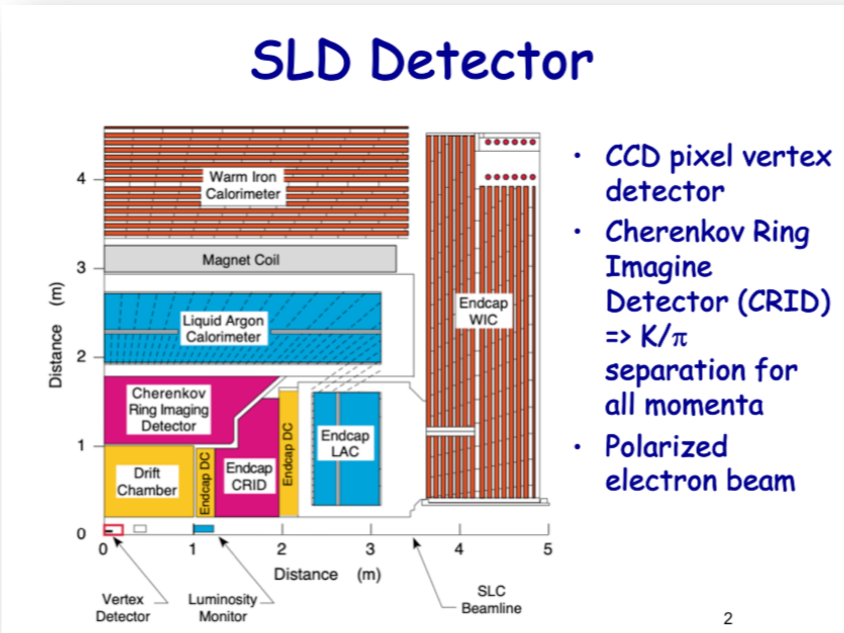
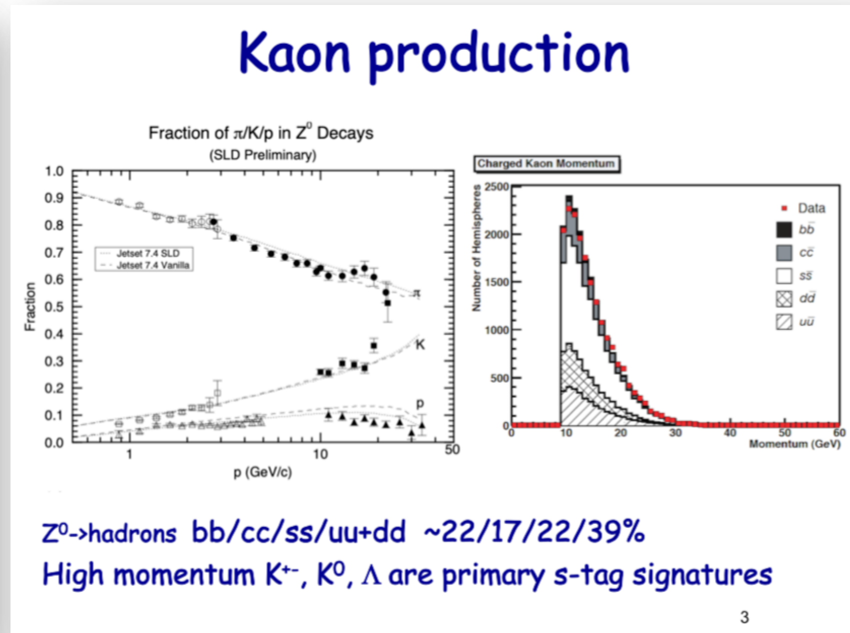
SLD

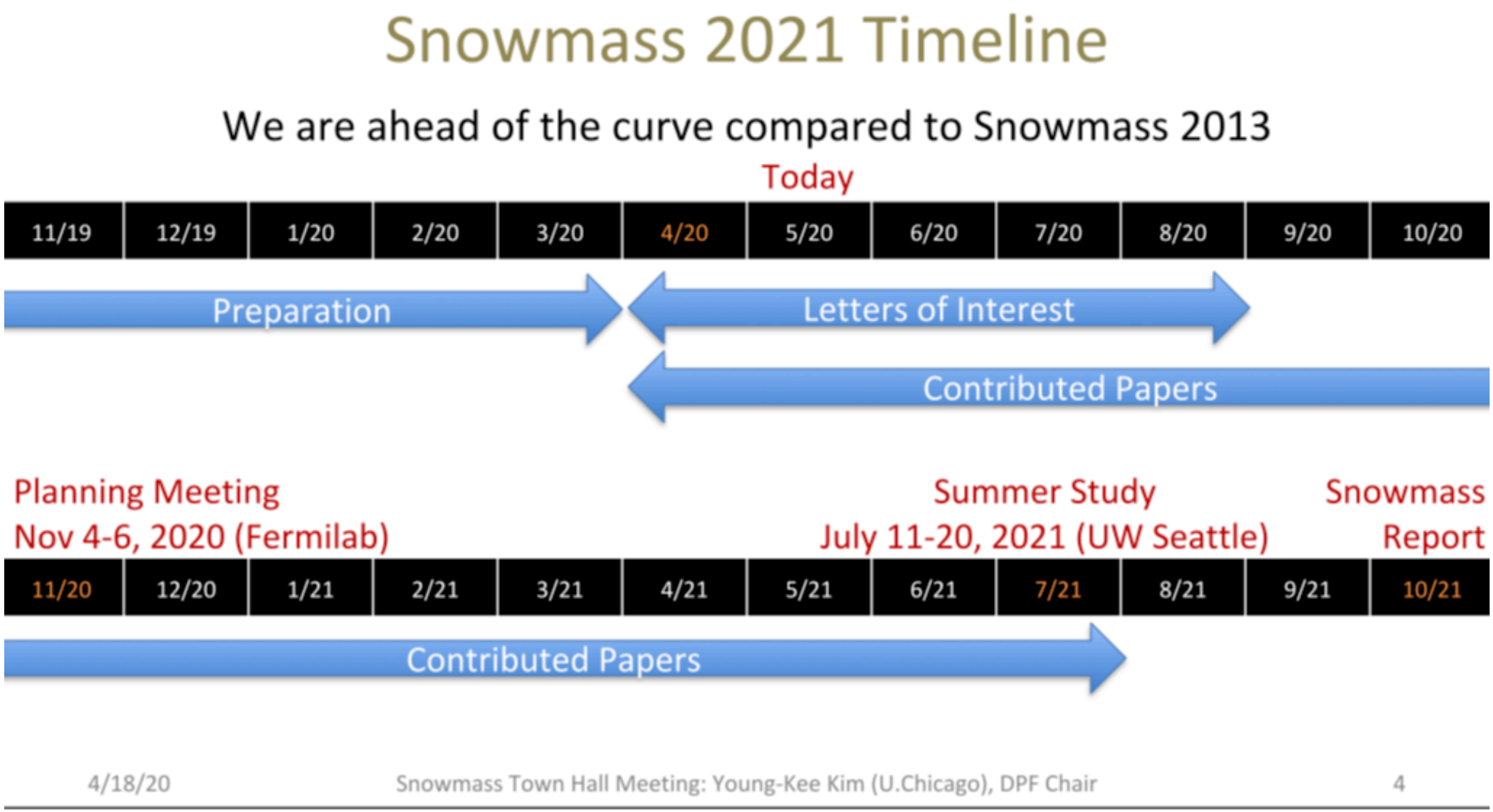
https://indico.slac.stanford.edu/event/6617/contributions/1443/attachments/683/1978/s-tag-SLD.pdf





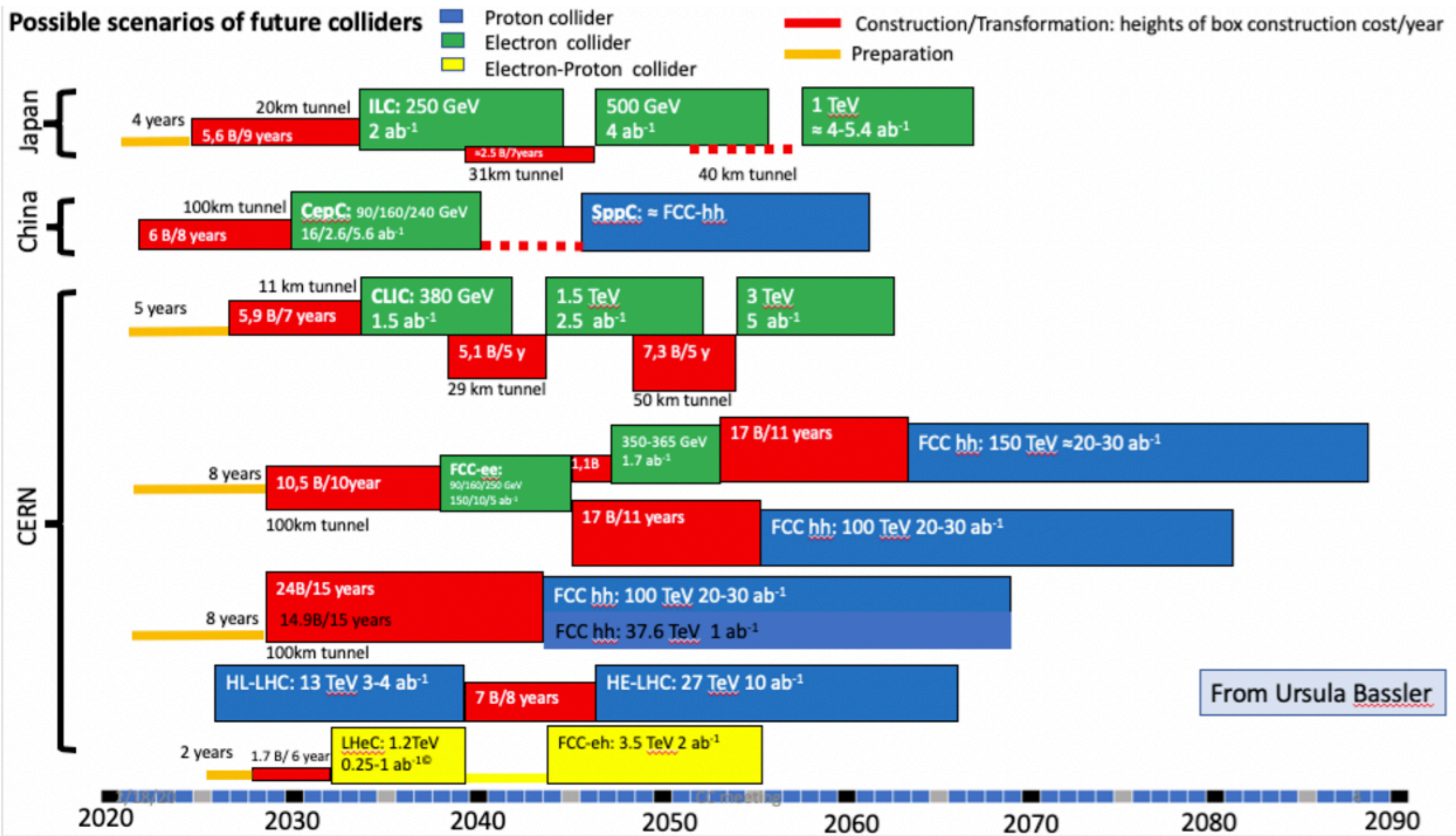
Snowmass Timeline

https://indico.fnal.gov/event/24264/contributions/75978/attachments/128521/155690/Energy-Frontier-Kick-off-meeting.pdf



Possible future colliders scenario

https://indico.fnal.gov/event/24264/contributions/75978/attachments/128521/155690/Energy-Frontier-Kick-off-meeting.pdf



Linear vs Circular colliders

- From the Energy Frontier workshop

Which Machine(s)?

Hadrons

- large mass reach ⇒ exploration?
- S/B ~ 10^{-10} (w/o trigger)
- S/B ~ 0.1 (w/ trigger)
- requires multiple detectors (w/ optimized design)
- only pdf access to $\sqrt{\hat{s}}$
- ⇒ couplings to quarks and gluons

Leptons

- S/B ~ 1 ⇒ measurement?
- polarized beams (handle to chose the dominant process)
- limited (direct) mass reach
- identifiable final states
- ⇒ EW couplings

Circular

- higher luminosity
- several interaction points
- precise E-beam measurement (O(0.1MeV) via resonant depolarization)
- $\sqrt{s}$ limited by synchroton radiation

Linear

- easier to upgrade in energy
- easier to polarize beams
- "greener": less power consumption*
- large beamsthralung
- one IP only

*energy consumption per integrated luminosity is lower at circular colliders but the energy consumption per GeV is lower at linear colliders

hristophe Grojean — Future Measurements — 9 — Inst. Pascal, Dec. 4, 2019

The ILC case

- **ILC Study Questions for Snowmass 2021**: https://arxiv.org/pdf/2007.03650.pdf

At this moment, we see an opportunity for the ILC to actually be constructed for operation in the 2030's. This makes it especially important today to understand and evaluate the ILC capabilities.

5 Questions about general e^+e^- event analysis

11. Particle ID. The SiD and ILD detectors do not have dedicated subdetectors for particle ID; however, they can identify kaons by dE/dx measurement or by track timing. Identification of kaons is important for many aspects of e^+e^- physics, including the vertex charge measurement described in the previous question and the reconstruction of τ leptons from their final states. It is then interesting to consider how kaon identification could be improved, for example, using the new timing detector technologies being developed for HL-LHC, and the implications for e^+e^- physics measurements. [miniDST].

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8. Higgs decays to light quarks. One can add to the previous question the possibility of Higgs decay to $s\bar{s}$, $d\bar{d}$, $u\bar{u}$. What limits on these modes can be achieved? Can $h \to s\bar{s}$, with $BR = 10^{-4}$ in the SM, be observed? A theoretical study on the discrimination of light quark and gluon initiated jets can be found in [63]. The possibility of observing $h \to s\bar{s}$ is discussed in [54] and in question #12 of Sec. 5. [miniDST]

13. Flavor-violating Higgs decays. What limits can be placed on $h \to \tau\mu$, $h \to bs$, and other flavor-violating fermion combinations? [miniDST]

The ILC case

- **ILC Study Questions for Snowmass 2021**: https://arxiv.org/pdf/2007.03650.pdf

At this moment, we see an opportunity for the ILC to actually be constructed for operation in the 2030's. This makes it especially important today to understand and evaluate the ILC capabilities.

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